VOL. 10, NO. 8, MAY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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OPTIMIZATION OF PERFORMANCE CHARACTERISTICS IN THE ABSORBER WITH TWISTED TAPES INSERTS OF PARABOLIC TROUGH COLLECTOR USING RESPONSE SURFACE METHODOLOGY

K. Syed Jafar and B. Sivaraman
Department of Mechanical Engineering, Annamalai University, Annamalainagar, Tamil Nadu, India
E-Mail:majallelku@gmail.com

ABSTRACT

A study is carried out with the experimental investigation of an absorber with twisted tape in solar parabolic trough collector to obtain optimum process parameters by Statistical tools such as design of experiments. In these study parameters as Reynolds number and twist ratio are optimized with the consideration of responses as the heat transfer and friction factor. From the results, it was observed that the significant increase augmentation in Nussle number and considerable friction factor can be obtained at high Reynolds number and low twist ratios parameters. Finally, from the experimental design and ANOVA using Design Expert software, it was found that the twist ratio is the major parameter that influences absorber of parabolic trough collector performance.

Keywords: solar parabolic trough collector, twisted tape, twist ratio, heat transfer, friction factor.

1. INTRODUCTION

Solar energy is an important alternative source of energy and preferred to other energy sources because it is abundant, inexhaustible and non-pollutant. Solar parabolic trough collectors (PTC) are used for variety of applications such as heating [1] and power generation [2]. Arasu and Sornakumar[3] studied the thermal performance of a fiberglass reinforced parabolic trough collector for hot water generation system.Premkumar *et al*.[4] investigated solar thermal energy stored in the therminol -55 oil on solar parabolic trough collector. Several significant performance improvements experiments on PTC system by new designs, others had been focused on improving the receiver tube reliability, selective coating performance, and accurate tracking mechanism.

Many active and passive augmentations are being used in heat transfer techniques for heat exchanger applications. Heat transfer in an absorber of parabolic trough collector could be enhanced by means of twisted tapes, inserted inside the fluid flow tubes, which induce swirl flow and act as turbulence promoters. Sandhu *et al*. [5] studied the performance of different geometrical shape and configurations twisted tape inserts fitted in flat-plate solar collector. The results show that the channel inclination does not have significant impact on the Nussle number enhancement. Also they concluded that the wire mesh insert thermally performed better at low Reynolds numbers however, a higher pressure drop is anticipated in the collector.Chean and Regano [6] conducted experiments using tubular absorbers fitted with helically coil/wire and twisted tape inserts. They observed from their study that the superior overall performance without substantial pressure penalty compared to that of tubes with coil or tape inserts. Ananth and Jaisankar [7] studied the effect of helical twist tape of different spacer of lengths (125,250 and 500 mm) on thermosyphon solar water heater. They reported from their results that the maximum increase in thermal performance is obtained from increased spacer length. Karthikeyan *et al*. [8] used RSM to develop the empirical relationships to predict the tensile shear fracture load of friction stir spot-welded AA2024 aluminium alloy. Kumar and Prasad [9] reported on the characteristics of heat transfer and friction factor of solar water heating system with twisted tapes. Sivashanmugam and Suresh [10] investigated the heat transfer enhancement and thermal performance factor in a heat exchanger tube fitted with helical screw-tape, regularly spaced helical screw-tape for both laminar regions. Raguraman *et al*. [11] used Taguchi method to optimize the performance evaluation of heat transfer coefficient for agitated vessel using coal slurry in coal gasification power plant. Many research works have been carried out the effect of HVOF spray characteristics parameters on coating by Response surface methodology (RSM) is widely used to solve the optimization [12-13].

In this study twist ratio, and Reynolds number are parameters and they play a significantly role in the absorber of PTC solar collector. Nussle number and friction factor are important responses as taken for increase the heat transfer and pressure drop of the system. Laminar flow heat transfer at low Reynolds number in a parabolic trough solar collector is major thermal resistance in the bulk flow in addition to the dominant thermal resistance in the thin boundary layer adjacent to the flow .Twisted tape inserts are, therefore, used to mix the gross flow effectively in laminar flow to reduce the thermal resistance in the core flow through the absorber tube.

2. EXPERIMENTAL SETUP

An Experimental PTC model has been developed to investigate heat transfer; friction factor and thermal performance of absorber fitted with nail twisted tape at outdoor condition. Figure-1 shows the solar schematic of parabolic trough concentrating collector system. It consists of a solar concentrator (PTC), a storage tank, a circulating

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pump, a flow meter and other controlling devices. The photographic view of the PTC system used in experimental investigation is shown in Figure-2. The concentrator of the present collector with a rim angle of 90° is constructed of steel. The receiver, which is placed along the focal line of the concentrator, is of a copper tube coated with black paint and is covered by a glass envelope for reducing thermal heat losses that can take place by radiation and convection. The main function of the absorber of a PTC is to absorb and transfer the concentrated radiation to the working fluid flowing through the tube. A pump circulates water from a collecting tank through the absorber tube of the solar collector and back to the collecting tank. The PTC is oriented with a tracking north-south axis.

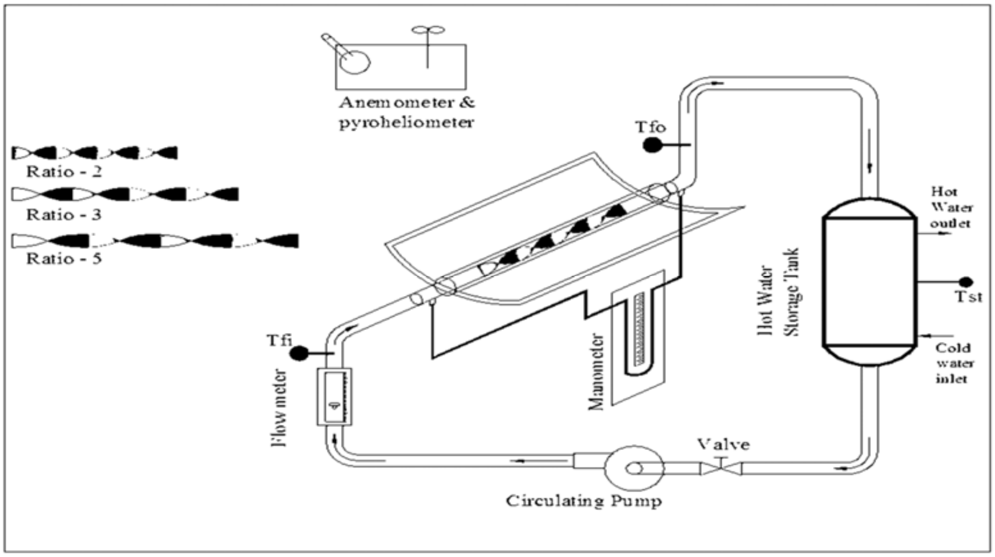

Figure-1. The schematic diagram of experimental setup.

Figure-2. Photograph of the experimental setup.

The storage tank is filled (up to half) from the main water supply. The Water temperatures at inlet and outlet of the absorber tube, water flow rate, and solar radiation intensity have been continuously measured during the experiment. Temperatures of water at inlet and exit of the absorber were measured using two calibrated. RTD PT 100 type temperature sensors of 0.1°C accuracy limited to digital indicator. The fluid mass flow rate was measured by rota meters. Isothermal pressure drops were measured by a U tube manometer. An Eppley pyrheliometer was used to measure the beam radiation intensity.

The plain twists used in the study were made up of thin, 1.5mm flat strip of aluminum. It has thickness of 11mm width and 2000mm length. The strips were twisted in the torsional twisting machine to the desired twisting ratio and were later inserted in to the absorber of PTC system.

Table-1. Solar PTC specifications used for investigation.

Receiver length (L)	2 m
Collector width (W)	1 m
Focal distance (F)	0.25 m
Receiver internal diameter ($D_{r,int}$)	12 mm
Receiver external diameter ($D_{r,ext}$)	12.5mm
Glass cover internal diameter ($D_{c,int}$)	18 mm
Glass cover external diameter ($D_{c,ext}$)	22 mm
Concentration ratio (C)	25.46
Receiver absorptance (α)	0.97
Absorber tube emissivity	0.25
Glass tube emissivity	0.94
Tracking mechanism type	Electronic

VOL. 10, NO. 8, MAY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

3. DATA ANALYSIS

In the experiments conducted the PTC was placed in a location with access to sunlight and throughout the experiment at period and the collector was kept with its absorber tracking the sun continuously so as to maximize the useful solar energy.

The heat transfer performance was defined in terms of the Nussle number (Nu) and an average value of heat absorbed by a fluid is taken for internal convective heat transfer coefficient (hi) given by

$$Nu = \frac{h\ D_i}{k} \quad (1)$$

In the present work, the pressure drop across the absorber was measured under isothermal flow conditions. It is used to calculate the friction factor using the following equation:

$$f = \frac{\Delta p}{\frac{1}{2}\rho\ u^2}\ \frac{D_i}{L} \quad (2)$$

Where, ΔP is the pressure drop across the absorber section, D_i is the inner diameter of tube, *u* is the velocity of water, and L is the length of tube. The Reynolds number is given by

$$R_e = \frac{uD_i}{\nu} \quad (3)$$

4. DEVELOPMENT OF A MODEL EQUATION FOR PERFORMANCE CHARACTERISTICS IN THE ABSORBER WITH TWISTED TAPES INSERTS OF PARABOLIC TROUGH COLLECTOR USING RSM

To find out the optimum levels of the most effective variables and to study their relationships, RSM using central composite design (CCD) was employed. RSM is a combination of mathematical and statistical techniques that are generally used for design of experiments, development of a mathematical model, identification of optimum combination of input parameters, and graphical expression of results for better understanding [14].

The relationship between the variables and the response after analysis was determined using the second order polynomial equation [15].

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j \quad (4)$$

Where Y is the predicted response, X_i, X_i^2, X_j are variables in coded values; β_0 is the constant; β_i is linear effect; β_{ii} is squared effect and β_{ij} is interaction effect. The analysis of results was performed with statistical and graphical analysis software (Design Expert, Version 8). The software was used for regression analysis of the data obtained and to estimate the coefficient of regression equation. In this study four variables were considered so k = 2, α = (2k) 1/4 = 1.

Based on the two-factor experimental results, two critical variables namely Reynolds number (Re) and twist ratio (T_w) were selected. For recording the responses due to changes in these variables, every selected variable were operated five coded levels (-1.41, -1, 0, 1, 1.41) and the values of these variables corresponding to these levels are shown in Table-2.

Table-2. Important function parameters and their levels.

No.	**Factor**	**Levels**				
		-1.41	**-1**	**0**	**1**	**1.41**
1	Reynolds Number	710	946	1182	1418	1654
2	Twist ratio	1	2	3	4	5

The performance of the absorber with twisted tape in solar parabolic trough collector should depend on all the non-dimensional parameters listed in the Table-3, however, the present work focuses only on the influence of variations in the Reynolds Number and Twist Ratio. The output performance parameters considered are Nussle Number and Friction factor.

Table-3. Non-dimensional parameters.

Non-dimensional expression	**Non-dimensional parameter**
$\frac{uD_i}{\nu}$	Reynolds number (R_e)
$\frac{h\ D_i}{k}$	Nussle number (Nu)
y/w	Twist ratio (T_W)
$f = \frac{\Delta p}{\frac{1}{2}\rho u^2}\frac{D_i}{L}$	Friction factor (*f*)

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Table-4. Design matrix and experimental results.

Process	Coded value		Original value		Response	
	Reynolds number	Twist ratio	Reynolds number	Twist ratio	Nussle number	Friction factor
1	-1	-1	946	2	10.0	0.0821
2	1	-1	1418	2	12.85	0.0611
3	-1	1	946	4	7.6	0.0791
4	1	1	1418	4	9.57	0.0560
5	-1.41	0	710	3	8.96	0.0918
6	1.41	0	1654	3	12.39	0.0619
7	0	-1.41	1182	1	11.37	0.0668
8	0	1.41	1182	5	7.33	0.0598
9	0	0	1182	3	9.83	0.0677
10	0	0	1182	3	9.82	0.0667
11	0	0	1182	3	9.84	0.0666
12	0	0	1182	3	9.83	0.0665
13	0	0	1182	3	9.84	0.0672

According to this design, the total number of experimental runs was $2k + 2k + x_0$, where k is the number of variables and x_0 is the number of repetitions of the experiments at the centre point. Thus, for this design, 13 experiments were performed according to the central composite design given in Table-4.

The responses are a function of Reynolds number (P) and Twist ratio (B) and it can be expressed as below.

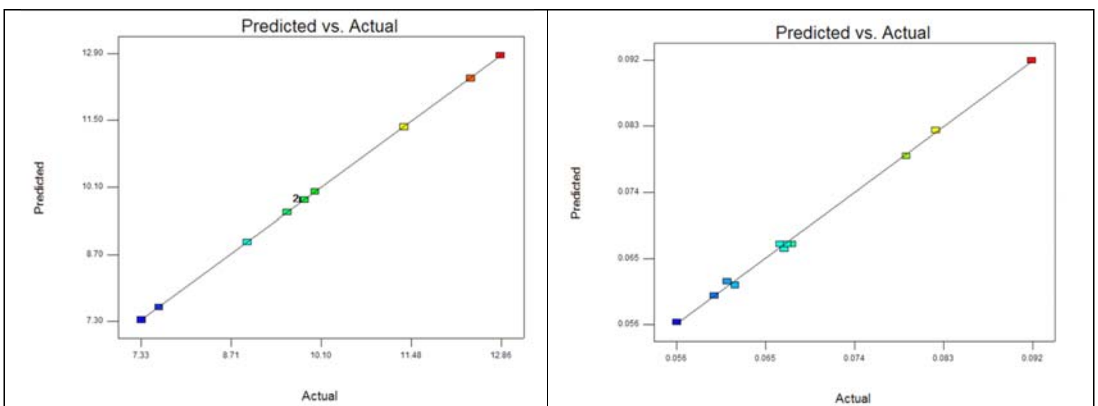
$$\text{Responses} = f(R_e, Tw) \quad (5)$$

For Nussle number and Friction factor responses, R_e, Tw, R_e^2 and T_w^2 are significant model terms. The final empirical relationship was constructed using only these coefficients and the developed final empirical relationship is given

$$\text{Nusselt number} = 9.83 + 1.21 * R_e - 1.42 * T_w - 0.22 * R_e * T_w + 0.42 * R_e^2 - 0.24 * T_w^2 \quad (6)$$

$$\text{Friction factor} = 0.067 - 0.011 * R_e - 2.249E\text{-}003 * T_w - 5.227E\text{-}004 * R_e * T_w + 4.848E\text{-}003 * R_e^2 - 1.902E\text{-}00 * T_w^2 \quad (7)$$

Figure-3 (a) and (b) shows the comparison of predicted results of Nussle number and Friction factor using the quadratic equation generated by RSM with the experimental values respectively. It is observed that there is acceptable qualitative and quantitative conformity between predicted values by the experimental values.



(a) (b)

Figure-3. Correlation plots for the responses.

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5. CHECKING THE ADEQUACY OF THE MODEL

In this investigation, analysis of variance (ANOVA) has been used to check the adequacy of the developed empirical relationships. ANOVA test results of the responses, namely, the Nussle number and Friction factor are presented in Tables 5 and 6, respectively.

Table-5.ANOVA for the response Nusselt number.

Source	Sum of squares	Df	Mean square	F Value	p-value Prob > F	
Model	29.96204	5	5.992408	64498.89	< 0.0001	Significant
A-Reynolds number	11.69043	1	11.69043	125829.2	< 0.0001	
B-Twist ratio	16.22626	1	16.22626	174650.3	< 0.0001	
AB	0.1936	1	0.1936	2083.801	< 0.0001	
A^2	1.22494	1	1.22494	13184.56	< 0.0001	
B^2	0.410353	1	0.410353	4416.809	< 0.0001	
Residual	0.00065	7	9.29E-05			
Lack of Fit	0.00037	3	0.000123	1.763572	0.2927	Not significant
Pure Error	0.00028	4	7E-05			
Cor Total	29.96269	12				
Std. Dev.	0.009639		R2		0.999978	
Mean	9.940769		Adj R2		0.999963	
C.V. %	0.096963		Pred R2		0.999898	
PRESS	0.003071		Adeq Precision		84.4351	

The model for Nusselt number response F-value of 64498.89 implies the model was significant. The Fisher's F test with a very low probability Value of "Probe>F" less than 0.0001 indicates high significance for the regression model terms. The "Lack of Fit F-value" of 1.76 implied the Lack of Fit was not significant relative to the pure error. Non-significant lack of fit is good. The coefficient of determination (R^2) for Nussle number calculated was 0.99, indicating that the value of the coefficient of variation (CV = 0.0969) indicated a better precision and reliability of the experiments. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Here, the ratio of 84.43 obtained in this model indicated an adequate signal.

Table-6.ANOVA for the response friction factor.

Source	Sum of squares	Df	Mean square	F value	p-value Prob > F	
Model	0.001182	5	0.000236	695.7853	< 0.0001	significant
A-Reynolds number	0.000932	1	0.000932	2741.759	< 0.0001	
B-Twist ratio	4.05E-05	1	4.05E-05	119.0501	< 0.0001	
AB	1.09E-06	1	1.09E-06	3.216116	0.1160	
A^2	0.000164	1	0.000164	481.16	< 0.0001	
B^2	2.52E-05	1	2.52E-05	74.04087	< 0.0001	
Residual	2.38E-06	7	3.4E-07			
Lack of Fit	1.37E-06	3	4.56E-07	1.800791	0.2865	not significant
Pure Error	1.01E-06	4	2.53E-07			
Cor Total	0.001185	12				
Std. Dev.	0.000583		R2	0.9979		
Mean	0.068753		Adj R2	0.9965		
C.V. %	0.847886		Pred R2	0.9904		
PRESS	1.13E-05		Adeq Precision	89.82928		

VOL. 10, NO. 8, MAY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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The model for Friction factor response F-value of 695.78 implies the model was significant. The Fisher's F test with a very low probability Value of "Prob>F" less than 0.0001 indicates high significance for the regression model terms. The "Lack of Fit F-value" of 1.80 implied the Lack of Fit was not significant relative to the pure error. Non-significant lack of fit is good. The coefficient of determination (R^2) for Friction factor calculated was 0.9979, indicating that the value of the coefficient of variation (CV = 0.8478) indicated a better precision and reliability of the experiments. Adeq Precision (89.82) indicated an adequate signal.

6. RESULTS AND DISCUSSIONS

6.1 Combined effect of operating parameters on the response

The Three-dimensional and contour response surfaces generated from the predicted results Eq. 2 and 3 and plots obtained from the Design Expert software are shown in Figures 4 (a-d).

The variation of Nussle number, the combined effect of Reynolds number and twist ratio was investigated as shown 3D surface and its corresponding contour plotted in Figure-4a-b. As can be seen, the Nussle number response increases when the twist ratio decrease with increase Reynolds number. Due to artificial turbulence exerted by twisted tape the heat transfer increases. The swirl flow caused by the twisted tape effectively increases the heat transfer. The Nussle Number is increases with decreasing twist ratio. This is also due to more intense swirl flow incase of lower twist ratio.

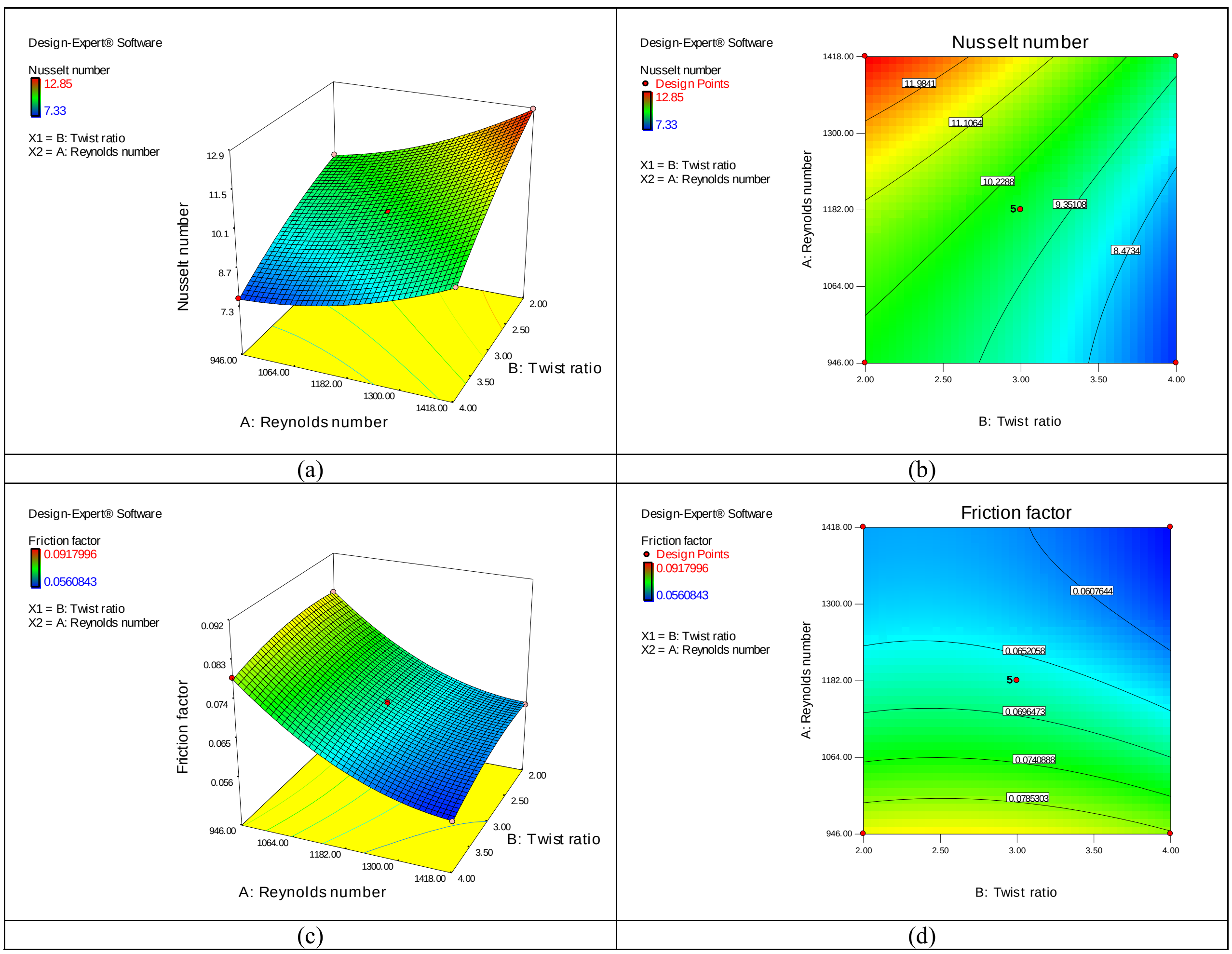

Figure-4. Design expert software figures.

Figure-4 (c)-(d) depicts the 3D plot and its corresponding contour plot to show the variation friction factor, the combined effect of Twist ratio and Reynolds number has been analyzed.The friction factor decreases with increase in Reynolds Number, because the swirl flow effect caused by the twist increases the wetted surface area and the dissipation of dynamic pressure of fluid at high viscosity loss near the tube wall. Due to this effect the fluid flow has high pressure loss in the twisted tape system. The friction factor increases with the decrease of twist ratio again due to swirl flow exerted by the twisted tape.

Figure-4 shows3D surface and contour plotted for combined effect of (a, b) Reynolds number and Twist ratio for Nussle number;(c, d) Reynolds number and Twist ratio for Friction factor.

7. CONCLUSIONS

In this paper, an attempt has been made to identify the proper non dimensional numbers associated with Response Surface Methodology (RSM) technique to investigate for Enhance heat transfer in the effects of absorber of solar trough collector with twisted tape inserts incorporating process parameters such as the Reynolds number (Re) and twist ratio of inserts (T_w) From the experimental study carried out it can be concluded that:

a) The condition these results used to develop empirical relationship to predict the Nussle number and friction factor as function of Reynolds number and twist ratio.
b) It is clear that minimum twist ratio (T_w= 2) enhances the heat transfer and maximize friction factor with increase Reynolds number.
c) The Nussle number increases with an increase in Reynolds number and with minimum Twist ratio.
d) The Friction factor decreases with an increase in Nussle number but increases with a decrease in Twist ratio. The optimal arrangement can be obtained through optimization of experimental design technique for the modeling and prediction of results due to its high accuracy and therefore, it can be used to simulate the experiments precisely.

Nomenclature

ANOVA	:	Analysis of variance
Di	:	Diameter of copper tube, m
f	:	Friction factor
h	:	Convective heat transfer co-efficient, W/m^2K
k	:	Thermal conductivity, W/m K .
Nu	:	Nussle number
Re	:	Reynolds number
w	:	tape width, m
u	:	bulk average fluid velocity (m/sec)
y	:	tape pitch length, m

Greek letters

ρ	:	Density, kg/m^3
γ	:	Kinematic viscosity, m^2/s
Δp	:	Pressure drop of fluid (N/m^2)

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